Perceptual Speed and IQ Are Associated Through Common Genetic Factors

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Individual differences in inspection time explain about 20% of IQ test variance. To determine whether the association between inspection time and IQ is mediated by common genes or by a common environmental factor, inspection time and IQ were assessed in an extended twin design. Data from 688 participants from 271 families were collected as part of a large ongoing project on the genetics of adult brain function and cognition. The sample consisted of a young adult cohort (mean age 26.2 years) and an older adult cohort (mean age 50.4 years). IQ was assessed with the Dutch version of the WAIS-3R. Inspection time was measured in the so-called Π-paradigm, in which a subject is asked to decide which leg of the Π-figure is longest at varying display times of the Π-figure. The number of correct inspections per second (i.e., the reciprocal of inspection time) was used to index perceptual speed. For Verbal IQ and Performance IQ, heritabilities were 85% and 69%, respectively. For perceptual speed, 46% of the total variance was explained by genetic variance. No differences in heritability estimates across age cohorts or sexes were found. Across the whole sample, a significant phenotypic correlation was found between perceptual speed and Verbal IQ (0.19) and between perceptual speed and Performance IQ (0.27). These correlations were entirely due to a common genetic factor that accounted for 10% of the genetic variance in verbal IQ and for 22% of the genetic variance in performance IQ. This factor is hypothesized to reflect the influence of genetic factors that determine axonal myelination in the central nervous system.

KEY WORDS: Neural speed; information processing; intelligence; extended twin design; inspection time.

INTRODUCTION

In 1996, Deary and Stough stated that "inspection time is, to date, the only single information processing index that accounts for approximately 20% of intelligence-test variance." Inspection time is defined as the minimum display time a subject needs to make an accurate perceptual discrimination on an obvious stimulus, and is often thought to reflect speed of apprehension or perceptual speed (Kranzler and Jensen, 1989). Visual inspection time is usually measured in the so-called Π-paradigm in which subjects are asked to decide which leg of the Π-figure is longest. There is no need to make this decision

quickly; all that is required is an accurate response. Display time of the Π-figure is varied in order to determine the display time at which a predefined percentage (e.g., 80%) of the subjects' answers is correct. The manipulation of display time (also called SOA; stimulus onset asynchrony) is usually implemented by using a backward masking method, i.e., covering the stimulus with a Π-figure of which both legs are equally long. This reduces after-image of the stimulus on the computer screen, which otherwise would have allowed subjects to gain time beyond the actual display time of the stimulus. The use of different masking methods or no mask at all may blur inspection time-IQ correlations, because smarter people may benefit more from after-image artifacts. A prerequisite for obtaining a reliable inspection time-IQ association is the use of a good mask (Knibb, 1992).

A meta-analysis conducted by Kranzler and Jensen (1989) indicated that inspection time and IQ correlate

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around -0.50: The less time a person needs to make an accurate decision on an obvious stimulus, the higher his or her IQ. Inspection time correlates somewhat higher with performance IQ (-0.54) than with verbal IQ (-0.40) and correlations seem constant over age (Kranzler and Jensen, 1989). It is attractive to hypothesize that inspection time indexes the speed of perceptual processing, or even central nervous (CNS) system processing in general, hence explaining its association with IQ. In fact, the primary idea behind studies investigating the correlation between inspection time and IQ has been that a faster brain should result in a smarter brain. If this idea holds true, then unravelling the determinants of interindividual variance in inspection time in adult humans may also cast light on factors that determine interindividual differences in IQ.

In the present paper, we investigate which factors (genetic or environmental) contribute most to interindividual variability in inspection time and which factors mediate the observed correlation between inspection time and IQ. An extended twin design (i.e., including families consisting of twins and additional siblings) is used to maximize statistical power to detect genetic and environmental influences (Posthuma and Boomsma, 2000).

METHOD

Subjects

Subjects were recruited from The Netherlands Twin Registry (Boomsma, 1998) and participated in a large and as yet ongoing project on the genetics of cognition and adult brain function.

Analyses are based on the 688 family members from a total of 271 extended twin families that had entered the study by December 2000. Fig. 1 depicts the age distribution of the complete sample showing it actually consisted of two cohorts: a young adult cohort with a mean of 26.2 (*SD* 4.19) years of age and an older adult cohort with a mean of 50.4 (*SD* 7.51) years of age. We did not want to rule out possible differential age effects on IQ or inspection time for the two age cohorts. For example, in the young cohort age may not have any effect at all on IQ, whereas in the older cohort a gradual decrease in IQ with age seems reasonable to expect. It was decided, therefore, to include cohort-status in the analyses. Allocation of a family member to one of the two cohorts (young cohort under 36 years of age, older cohort above 36 years of age) was based on the age of the twins. There was a slight overlap in age of the non-twin siblings between the two cohorts.
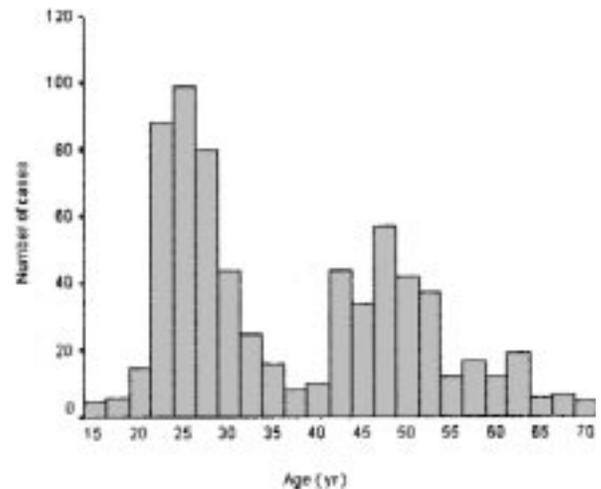

Fig. 1. Age distribution ($N = 688$) showing two cohorts.

Table I lists the complete sample configuration. For example, in the young cohort, 20 MZ families consisting of a complete MZ pair and one additional sibling participated. Participating family members ranged from 1 to 8, with an average of 2.5 subjects per family. In the young cohort, 171 males and 210 females participated, in the older cohort 135 and 172, respectively.

Table II lists the specific distribution of sex, age, educational level, and zygosity groups within the two cohorts.

The Dutch classification system for education level (Standaard Onderwijs Indeling [SOI], 1998) follows the International Standard Classification of Education (ISCED, 1997). The Dutch standard has seven categories, ranging from primary education (category 1) through tertiary education (category 7). The average SOI educational level was 4.21 (*SD* 1.05), meaning that on average subjects received schooling until 16 years of age, which is compatible with the general Dutch population (CBS, 2000). The subjects in the young cohort had a significantly higher average education category (mean 4.4, *SD* 1.03) than subjects in the older cohort (mean 4.0, *SD* 1.04). The same was true for males (mean 4.3, *SD* 1.04) and females (mean 4.1, *SD* 1.03). This pattern was also compatible with males and females of different ages in the general Dutch population (CBS, 2000).

Task and Variables

Inspection Time

A Parameter Estimation by Sequential Testing (PEST) procedure (Findlay, 1978; Pentland, 1980) was

Table I. Family Configuration in the Sample According to Zygosity, Cohort, and Number of Additional Non-Twin Siblings

						Additional siblings							
	0		**1**		**2**		**3**		**4**		**6**		
	fams	*ss*	fams	*ss*	fams	*ss*	fams	*ss*	fams	*ss*	fams	*ss*	
Young cohort													
MZ twin pair	31	*62*	20	*60*	2	*8*	1	*5*	—	—	—	—	Total MZ pairs: 54
single twin	1	*1*	3	*6*	—	—	—	—	—	—	—	—	
DZ twin pair	16	*32*	24	*72*	7	*28*	—	—	—	—	—	—	Total DZ pairs: 47
single twin	1	*1*	4	*8*	1	*3*	—	—	—	—	—	—	
DOS twin pair	11	*22*	12	*36*	2	*8*	1	*5*	—	—	—	—	Total DOS pairs: 26
single twin	2	*2*	4	*8*	1	*3*	—	—	1	*5*	—	—	
no twins	—		2	*2*	2	*4*	—	—	—	—	—	—	
Total Young	62	*120*	69	*192*	15	*54*	2	*10*	1	*5*	—	—	Total additional siblings: 109
Older cohort													
MZ twin pair	26	*52*	16	*48*	4	*16*	1	*5*	—	—	1	*8*	Total MZ pairs: 48
single twin	2	*2*	3	*6*	—	—	—	—	1	*5*	—	—	
DZ twin pair	20	*40*	15	*45*	1	*4*	—	—	—	—	—	—	Total DZ pairs: 36
single twin	3	*3*	1	*2*	2	*6*	—	—	—	—	—	—	
DOS twin pair	11	*22*	8	*24*	2	*8*	—	—	1	*6*	—	—	Total DOS pairs: 22
single twin	2	*2*	1	*2*	—	—	—	—	—	—	—	—	
no twins	—	—	1	*1*	—	—	—	—	—	—	—	—	
Total Older	64	*121*	45	*128*	9	*34*	1	*5*	2	*11*	1	*8*	Total additional siblings: 80
Total	126	*241*	114	*320*	24	*88*	3	*15*	3	*16*	1	*8*	

Note: Fams = number of families, ss = number of subjects, MZ = monozygotic twins, DZ = dizygotic same sex times, DOS = dizygotic opposite sex twins. Example: In the young cohort, 24 families consisting of a full DZ pair and one additional sibling participated (72 subjects). In the complete sample, 114 families consisting of one additional sibling and either a complete or an incomplete twin pair participated.

Table II. Descriptives of the Two Cohorts by Zygosity and Sex

	ss	Age range (yrs)	Mean age (SD) (yrs)	Education (SOI* categories)
Young cohort				
MZM	50	22.4–33.9	26.0 (3.07)	4.6 (1.14)
MZF	62	22.5–33.9	25.5 (3.42)	4.1 (0.93)
DZM	38	21.8–30.0	26.0 (2.13)	4.5 (0.76)
DZF	62	22.5–33.4	25.8 (2.72)	4.7 (0.92)
DOS	60	18.8–31.8	25.4 (2.87)	4.4 (0.85)
Add. siblings-males	54	13.9–42.6	27.3 (6.67)	4.0 (1.02)
Add. siblings-females	55	16.7–39.3	27.3 (5.85)	4.5 (1.03)
Total	*381*	*13.9–42.6*	*26.2 (4.19)*	*4.4 (0.95)*
Older cohort				
MZM	48	36.0–69.1	49.1 (6.92)	4.3 (1.09)
MZF	53	42.2–67.4	52.5 (7.8)	3.8 (0.96)
DZM	26	42.7–64.1	52.4 (5.07)	4.3 (1.37)
DZF	52	42.1–62.7	50.5 (6.21)	3.7 (1.09)
DOS	47	41.6–71.0	49.8 (7.98)	4.2 (1.09)
Add. siblings-males	37	37.0–68.4	50.8 (8.48)	4.3 (1.09)
Add. siblings-females	44	29.1–70.9	48.3 (8.50)	3.6 (0.97)
Total	*307*	*29.1–71.0*	*50.4 (7.51)*	*4.0 (1.11)*

*SOI = Dutch standard classification system; ss = number of subjects.

incorporated into a Π-paradigm following the description in Luciano *et al.* (2001). Briefly, the PEST procedure uses a staircase method in which stimulus duration is altered based on the subjects' response. If a correct answer is given, stimulus duration time of the next trial is decreased; if an incorrect answer is given, stimulus duration of the next trial is increased. The amount of increase or decrease is dependent on the number of previous reversals of increase/decrease. Thus, after many reversals, increases and decreases on subsequent trials become smaller and the PEST procedure converges on the subjects' inspection time. The task ends when the PEST estimate has become sufficiently stable or as soon as the maximum number of trials is presented.

For each subject, a cumulative normal function (mean = 0) was fitted *post hoc* to the stimulus duration times. The *SD* of this curve is the SOA at which 84% accuracy (corrected for guessing) is achieved (as described in detail in Luciano *et al.* 2001). The reciprocal of the *SD* $\times$ 1000 can be interpreted as the number of inspections per second resulting in a correct judgement (Smith, 2000). This measure was used throughout this paper and will be referred to as *perceptual speed.* In contrast to inspection time itself, the number of correct inspections per second or perceptual speed is expected to correlate positively with IQ, i.e., a high value on perceptual speed means that more correct perceptions per time unit are made and refers to a fast inspection time.

To ensure accurate SOAs, a dynamic backward mask (Evans and Nettelbeck, 1993) was used (Fig. 2). All instructions were given on a computer screen and the importance of accuracy over reaction time was stressed in the instruction.
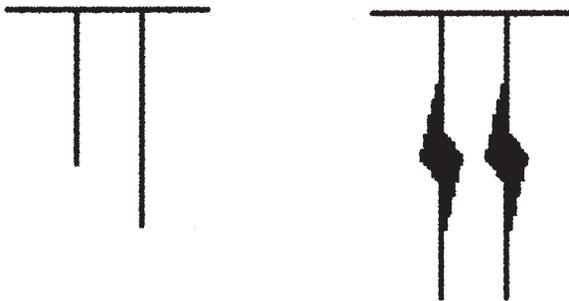
Fig. 2. Π-paradigm with backward masking; the Π is briefly presented and covered with the mask. The amount of increase/decrease of stimulus duration in each trial is dependent on whether or not the subject answered correctly or incorrectly in the previous trials (see text also).

Intelligence Testing

IQ was measured with the Dutch adaptation of the WAIS-3R (WAIS-III, 1997). Standardization norms for this version are currently being determined and at this point it is not possible to report standard IQ scores. Performance IQ was calculated as the mean of three subtests (picture completion, block design, matrix reasoning) and verbal IQ was based on the mean score on four subtests (information, similarities, vocabulary, arithmetic).

Statistical Analysis

Because the sample consisted of unbalanced pedigrees and had some missing data, models were fitted to the raw data rather than covariance matrices. This was accomplished by using the rectangular data file option in Mx (Neale, 1997). Saturated models were fitted in order to determine the fit of the variance components models. The saturated models included modeling a linear regression effect of age within each cohort and a deviation for males within each cohort. The significance of these effects of the means were estimated in the saturated models and the following assumptions of the (extended) twin method were tested: (1) heterogeneity of variances across MZ twins, DZ twins, and siblings, across males and females, and across cohorts; (2) heterogeneity of correlations across MZM twins and MZF twins, and across DZM twins, DZF twins, DOS twins, and sib-sib male/female pairings; (3) heterogeneity of DZ correlations and sib-sib correlations; (4) differences in means between MZ twins, DZ twins, and siblings; and (5) differences in means between cohorts. The resulting most parsimonious saturated model is the model against which the variance components models are tested.

In the variance components models, the observed variance was decomposed in three of four possible latent sources of variance: additive genetic (A), non-additive genetic (D), shared environment (C), and non-shared environment (E) following Neale and Cardon (1992). For DZ twins (and sib pairs if the saturated models indicated no difference in correlation between DZ pairs and sib pairs) similarity in shared environmental influences was fixed at 100%, similarity of additive genetic influences at 50%, similarity of non-additive genetic influences at 25%, and no similarity in non-shared environmental influences. For MZ twins similarities of additive genetic, non-additive genetic and shared environmental influences were fixed at 100% and no similarity in non-shared environmental influences.

Results

Twenty seven subjects of the total 688 subjects took an IQ test at home and did not have data on the computerized inspection time task. Ten subjects who came to the laboratory were unable to perform the inspection time task due to a lack of time or computer problems. Inspection time results from another 10 subjects were discarded from the analyses because they had an unusual long inspection time (2000 ms), which raised the suspicion that they did not perform the task as intended. This left 688 subjects with IQ data of whom 641 also had data on perceptual speed.

Saturated Model Fitting Results and Descriptives

The saturated model fitting procedures indicated that for perceptual speed, Verbal IQ and Performance IQ (1) the variances were homogenous across sexes and across zygosity; (2) the MZF and MZM correlations were homogenous; (3) the DZM, DZF, and DOS correlations were homogenous, and the DZ correlations and sibpair correlations were homogenous; (4) no differences in means were found between MZs, DZs and sibs; and (5) the variances and twin correlations across cohorts were homogenous.

Table III shows the significant effects on the means in the most parsimonious trivariate saturated model. Males performed better on all three measures in both the young and the old cohort, except for perceptual speed, where males and females scored equally well. The difference in means between males and females was larger in the older cohort compared with the young cohort. In the young cohort, there was no effect of age on perceptual speed and Performance IQ. On Verbal IQ every year would raise the score with 0.22 points, i.e., being 25 years of age adds 0.22 * 25 = 5.5 to the grand mean. In the old cohort, for all three measures a higher age decreases the score.

The grand means were equal for both cohorts except on Verbal IQ. Although the sign of the deviation of the old cohort is positive, this does not correspond to a higher mean in the older cohort compared with the young cohort. This can easily be demonstrated by calculating the expected scores for a female aged 26.2 years (i.e., the average age in the young cohort) and a female aged 50.4 years (the average age in the old cohort). For the 26.2-year-old female, the expected verbal IQ score is $22.70 + (0.22 * 26.2) = 28.46$, whereas for the 50.4-year-old female, the expected verbal IQ score is $22.70 + 6.55 - (0.07 * 50.4) = 25.72$.

The phenotypic correlations between the three measures were homogeneous over cohorts, sex, and zygosity. The correlation between perceptual speed and Verbal IQ was 0.19, between perceptual speed and Performance IQ was 0.27, and the correlation between Verbal IQ and Performance IQ was 0.49. These were all statistically significant at the 0.01 level.

Twin and sibling correlations were also homogeneous over cohorts and sexes, and there was no difference between DZ correlations and sib-correlations. The MZ and DZ correlations (and 95% CI) for perceptual speed were 0.48 (0.31 − 0.60) and 0.20 (0.10 − 0.31), respectively, for Verbal IQ 0.84 (0.79 − 0.88) and 0.47 (0.37 − 0.55), respectively, and for Performance IQ 0.69 (0.58 − 0.77) and 0.32 (0.22 − 0.42), respectively. The overall pattern of correlations indicates additive genetic influences and perhaps some common environmental influences.

Variance Components Modelling

The minus two log likelihoods (-2LLs) of the nested trivariate variance components models were compared to the -2LLs of the final saturated model by way of likelihood ratio test. In this way, a measure of goodness of fit of the variance components models was obtained.

The full trivariate ACE model fitted reasonably well with a chi-square of 0.78 compared with the sat-

Table III. Grand means, Standard Deviations (SD), and Effects on the Means of Perceptual Speed, Verbal IQ, and Performance IQ (as estimated with ML in the final saturated trivariate model)

	Grand mean	SD	Deviation of older cohort	Regression weight of age in young cohort	Regression weight of age in older cohort	Deviation of males in young cohort	Deviation of males in older cohort
Perceptual Speed	14.16	4.67	—	—	−0.05	—	1.70
Verbal IQ	22.70	5.41	6.55	0.22	−0.07	1.00	2.89
Performance IQ	23.63	3.63	—	—	−0.09	1.10	1.46

urated model and the same amount of degrees of freedom. However, shared environmental influences could be dropped from the model without significantly worsening the fit of the model ($\chi^2_6 = 2.82$). For the same reason, all common non-shared environmental factors could be dropped from the model ($\chi^2_3 = 3.22$). In contrast, the common genetic factors could not be dropped from the model without significantly worsening the fit. Dropping the common genetic factor for perceptual speed and Verbal IQ resulted in a χ^2 of 11.06 with one degree of freedom, for the common genetic factor between perceptual speed and Performance IQ the χ^2 with one degree of freedom was 18.18, and for the common genetic factor between verbal IQ time and performance IQ the χ^2 with one degree of freedom was 31.62.

Thus, a trivariate model that included additive genetic influences and non-shared environmental influences, and that allowed all phenotypic correlation between the three measures to be explained by common additive genetic factors fitted the data best. Fig. 3 illustrates this model and the standardized path coefficients.

As can also be calculated from Fig. 3 (see Neale and Cardon, 1992), the percentage of variation explained by additive genetic factors for perceptual speed, Verbal IQ, and Performance IQ was 46% (95% CI 33–58), 85% (80–89) and 69% (60–77), respectively. The remaining variation explained by non-shared unique environmental influences was 54% (42–67),
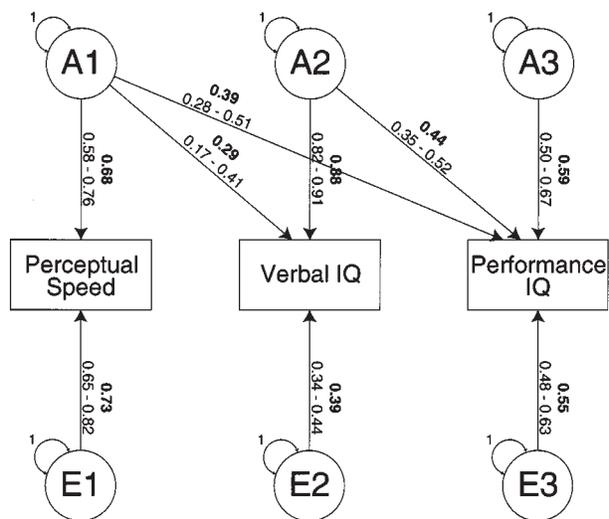
15% (11–20), and 31% (23–40) for perceptual speed, verbal IQ, and performance IQ.

The genetic correlation between perceptual speed and Verbal IQ was 0.31 (0.18–0.44). Or in other words, 10% of the genetic variance in Verbal IQ is explained by genetic factors that are shared with perceptual speed. The genetic correlation between perceptual speed and Performance IQ was 0.47 (0.33–0.61), indicating that 22% of the genetic variance in performance IQ was explained by genetic factors shared with perceptual speed.

Not surprisingly, a high genetic correlation was also observed between Verbal IQ and Performance IQ; 0.65 (0.56–0.72), corresponding to 28% of the genetic variance in Performance IQ that is shared with genetic factors important to Verbal IQ. This also means that 50% of the genetic variance in Performance IQ is unique to Performance IQ, and thus unshared with either perceptual speed or Verbal IQ.

DISCUSSION

In a large sample of 688 individuals, the phenotypic correlation between the number of correct inspections per second and Verbal IQ was 0.19 and between the number of correct inspections per second and Performance IQ was 0.27. The magnitudes of these correlations are lower than the current consensus (e.g., Nettelbeck, 1987; Kranzler and Jensen, 1989) that sets the correlation between inspection time and IQ around −0.50 (the difference in sign simply reflects the reverse scaling of the number of correct inspections per second in comparison to inspection time). A possible source of difference is the use of different strategies by our subjects that may blur inspection time-IQ correlations (Knibb, 1992). This is not likely because a backward masking procedure was used to prevent the use of strategy. Furthermore, it has been shown that if strategies are used, the inspection time–IQ relation tends to be lower rather than higher than when no strategies are used (Deary and Stough, 1996).

It remains unclear why the inspection time–IQ relation in our sample is below the estimate derived from the meta-analysis (Kranzler and Jensen, 1989). It should be pointed out that the uncorrected correlations in this meta-analysis were very comparable to ours (around −0.30). Only when an attempt was made to correct for artifact effects inherent in pooling over studies for conducting a meta-analysis the corrected inspection time–IQ correlations came into the −0.50 range. Two sources of evidence suggest that the lower estimates for phenotypic inspection time–IQ correlation may be more

Fig. 3. Standardized estimates (95% CI) in best-fitting trivariate model. Reported values are estimated simultaneously with effects of age and sex on the observed scores.

correct. First, the number of subjects in this study (688) is larger than the total number of subjects used in the meta-analysis ($n = 88$ for PIQ, $n = 218$ for VIQ, and $n = 633$ for total IQ). Second, our results are consistent with findings from another recent large study, which included 390 twin pairs aged 16 years (Luciano *et al.,* 2001). In this study, a phenotypic correlation between inspection time and IQ of -0.36 was found.

Variance components analysis suggested moderate genetic influences on perceptual speed as indexed by inspection time; 46% of the interindividual variance was explained by genetic variance and 54% was explained by non-shared environmental sources of variance including measurement error. Shared environmental sources of variance did not significantly contribute to the interindividual variance. This pattern was uniform over two age cohorts and over both sexes. The influence of genetic variation on interindividual variation in IQ was much higher; 85% and 69% for Performance IQ and Verbal IQ, respectively, with the estimates uniform over cohorts and sexes. The observed correlation between our measure of perceptual speed and the two IQ measures was mediated completely by the sharing of underlying genetic factors; 10% of the genetic variance in Verbal IQ was explained by genetic factors shared with perceptual speed. Twenty-two percent of the genetic variance in performance IQ was explained by genetic factors shared with perceptual speed. These results are similar to the results obtained by Luciano *et al.* (2001) in a sample of 16-year-old twins.

Although no structural biological theories exist which specifically address inspection time, the existing biological model for visual processing based on the monkey brain holds strong clues to the possible source of genetic influences on perceptual speed/inspection time. Fig. 4 briefly explains this model.

A recent meta-analysis on the latencies of responses evoked by visual stimuli in the monkey, mostly obtained by intracranial electrophysiological recordings, showed that earliest responses in the lateral geniculate nucleus of the thalamus occurred at 28 to 31 msec, earliest responses in the primary and extrastriate visual cortices at 35 (V1), 54 (V2), and 61 (V4) msec, and earliest responses in the posterior part of the inferior temporal cortex (TE1) at 57 msec (Lamme and Roelfsema, 2000). Presumably, activation of V2 and inferior temporal cortex is minimally required when discriminating a simple two-dimensional object such as the Π figure. These latencies of the early visual pathways in monkeys compare quite reasonably to the earliest visual evoked potentials over the occipital cortex that occur around 60 msec (Celesia, 1993).

The interest in inspection time in intelligence research is driven mainly by the notion that it indexes a basic process in brain function, like perceptual, or even general information processing speed (Jensen, 1993; Eysenck, 1995), although this notion has been debated (Stankov and Roberts, 1997). If differences in inspection time reflect perceptual speed, then Fig. 4 reveals that a major source for genetic influences are the conduction velocity in the optic nerve to the thalamic LGN and the projection of LGN neurons to the primary cortex, and on to extrastriate areas. Optic nerve conduction velocity and conduction velocity from LGN neurons to higher areas depend on the fibre diameter of the axons, the number and form of ion channels in the axon membrane, and the quality (thickness and stability) of the myelin sheath generated by the oligodendrocytes (Kandel *et al.,* 1991). We hypothesize that part of the common genetic factors underlying IQ and inspection time are factors that determine myelination of axons by oligodendrocytes. Results from aging studies have indicated that, with aging, white matter (which is mainly composed of myelinated axons) density tends to decrease, whereas gray matter (cell bodies) density remains stable (Courchesne *et al.,* 2000). This suggests that aging does not result in neuronal apoptosis but instead goes along with a reduction in myelin, either by thinning of myelin sheaths or axonal degeneration. This will influence axonal conduction velocity and may explain the reduction in inspection time in the older cohort compared with the young cohort in this study.

Several genes that influence CNS axonal myelination have been implicated from animal models, some of which are known to cause dysmyelination in humans as well. The *Plp* gene (Xq22.3), for example, codes for two membrane proteins important for myelination. Disruption of expression of the *Plp* gene in mice causes a disruption in the assembly of the myeline sheath, which leads to a profound reduction in conduction velocity of CNS axons (Boison and Stoffel, 1994; Griffiths *et al.,* 1995, Ikenaka and Kagawa, 1995; Lemke, 1993). The influence of the *Plp* gene is specific to CNS axonal myelination because it does not affect peripheral conduction velocity nor give rise to gross behavioral anomalies (Boison and Stoffel, 1994). Although the exact role of the *Plp* gene in the CNS remains poorly defined (Knapp, 1996; Griffiths *et al.,* 1998), mutations in the same gene in humans are known to result in Pelizaeus-Merzbacher disease (PMD) (e.g., Anderson *et al.,* 1999; Griffths *et al.,* 1995; Woodward and Malcolm, 1999).
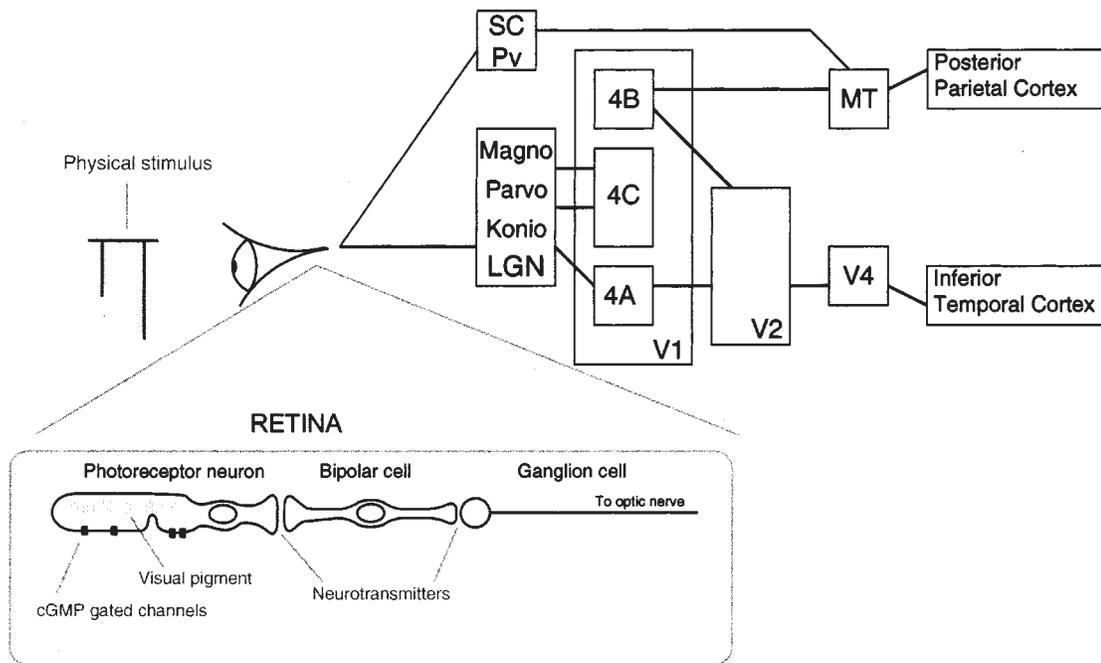
Fig. 4. The visual pathway in monkeys. Visual information processing-starts with the absorption of light by the visual pigments in the pho-toreceptors of the retina. This stimulates cGMP (cyclic nucleotide 3′–5′ cyclic gunosine monophosphate) phosphodiesterase, which reduces the amount of cytoplasmic cGMP and closes the cGMP gated channels, changing the ionic current across the membrane. This, in turn, leads to a hyperpolarization of the photoreceptor membrane and results in the reduction of glutamate in the synaptic cleft between photoreceptor and in-terneuron. The interneuron then transduces the electrical signal by way of graded potentials, eventually triggering an action potential in the ganglion cell. The axons of the ganglions cells leave the retina at the optic disc, where they become myelinated by oligodendrocytes and form the optic nerve (Tessier-Lavigne, 1991). That oligodendrocytes are a source of optic nerve myelination contrasts with other peripheral nerves where myelin is always generated by Schwann cells; this makes the optic nerve a good model for central nervous system conduction velocity.

   Most detailed anatomical information exists on the monkey brain (Kandel *et al.,* 1991; Salin and Bullier, 1995). Information from both eyes is conducted through neurons in the optic tract to the lateral geniculate nucleus (LGN) of the thalamus. Retinal information also travels to the pretectal area of the midbrain for the control of pupillary constriction, to the superior colliculus (SC), the pulvinar (Pv) for the control of (sac-cadic) eye movements, and to the cerebellum to control movement in response to visual input. The lateral geniculate nucleus projects to layer 4 of the primary visual cortex (V1) that projects on to V2 and higher visual association cortices (V4, MT), eventually leading to visual aware-ness. From the retina to the LGN and from the LGN to the area V1, parallel pathways (magno-, parvo-, and koniocellular) transfer different kinds of information that are recombined in areas V1 and V2. After recombination, two pathways emerge: a dorsal, magno-dominated pathway to the posterior parietal cortex involved with space and movement, and a ventral, parvo-dominated pathway concerned with object identifica-tion and perception to the inferior temporal cortex.

PMD is a hypomyelination disease which, in its mildest form, may lead to optic atrophy and dementia. Other genes implicated to be important for myelination in knock out mouse studies are the *cgt gene* (Stoffel and Bosio, 1997), the *MAG* gene (Fujita *et al.,* 1998, Sheikh *et al.,* 1999; Bartsch, 1996, for a review), and the *tn-r* gene (Weber *et al.,* 1999).

   Obviously, as is apparent from Fig. 4, aspects of visual processing other than conduction velocity de-termine inspection time as well. Speed of receptor po-tential generation in the photoreceptors and its trans-duction to ganglion cells depends on the availability of cGMP, the number of cGMP gated channels, and the availability of glutamate—factors that may well be under genetic control. Most important, the efficiency of synaptic neurotransmission in the LGN and striate neurons is a major determinant of visual processing speed. Given the staggering amount of protein interac-tions involved in neurotransmission, it is easy to envi-sion how synaptic transmission could introduce genetic variance in inspection time (and IQ). In fact, a sodium channel isoform was recently identified that influenced both axonal conduction velocity as well as synaptic re-sponses (Caldwell *et al.,* 2000). Finally, although in-spection time seems to depend largely on the "fast feed-forward sweep of visual information processing," we

cannot rule out effects of horizontal connections within the visual layers, e.g., within V1, or of recurrent processing from hierarchically higher visual areas (Lamme and Roelfsema, 2000), which brings in a number of possible additional genetic factors.

In summary, we found that the correlations between perceptual speed and Verbal IQ and between perceptual speed and Performance IQ were entirely due to a common genetic factor that accounted for 10% of the genetic variance in Verbal IQ and for 22% of the genetic variance in Performance IQ. We conclude that perceptual speed as indexed by inspection time can be used as an intermediate phenotype in linkage and association studies aimed at detecting genetic loci that determine interindividual variance in intelligence. Genes related to CNS axonal conduction velocity constitute good candidate genes for intelligence.

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